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Maeda

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(54) **MOTOR CONTROL APPARATUS THAT GENERATES PRELOAD TORQUE VALUE AS FUNCTION OF MOTOR ACCELERATION**

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H02P 5/46 (2006.01)

(52) **U.S. Cl.**
CPC ***F02D 25/00*** (2013.01); ***G05B 19/404*** (2013.01); ***H02P 5/46*** (2013.01); *G05B 2219/41264* (2013.01); *G05B 2219/41265* (2013.01); *G05B 2219/41426* (2013.01); *G05B 2219/50216* (2013.01)

(58) **Field of Classification Search**
CPC G05B 19/404; G05B 2219/41078; G05B 2219/50216; G05B 2219/50218; G05B 2219/50234
See application file for complete search history.

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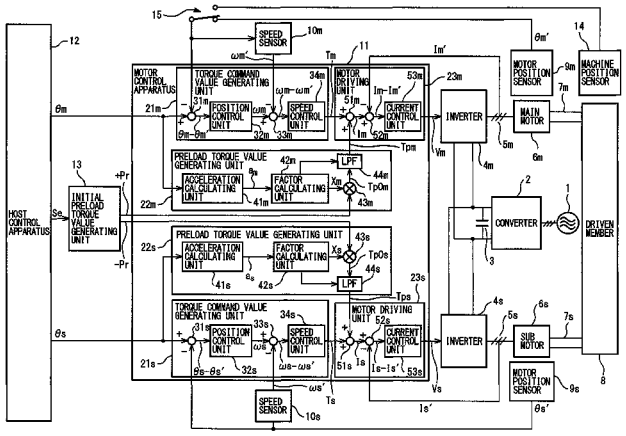
(57) **ABSTRACT**

A preload torque value generating unit (**22***m*) generates a preload torque value (Tpm) as a function of the acceleration (a_m) of a main motor (**6***m*), the preload torque value (Tpm) being a torque value that is appended in advance to a torque command value (Tm) so that the direction of force applied to the main motor (**6***m*) and the direction of force applied to a sub motor (**6***s*) will become opposite to each other. A preload torque value generating unit (**22***s*) generates a preload torque value (Tps) as a function of the acceleration (a_s) of the sub motor (**6***s*), the preload torque value (Tps) being a torque value that is appended in advance to a torque command value (Ts) so that the direction of force applied to the main motor (**6***m*) and the direction of force applied to the sub motor (**6***s*) will become opposite to each other.

3 Claims, 7 Drawing Sheets



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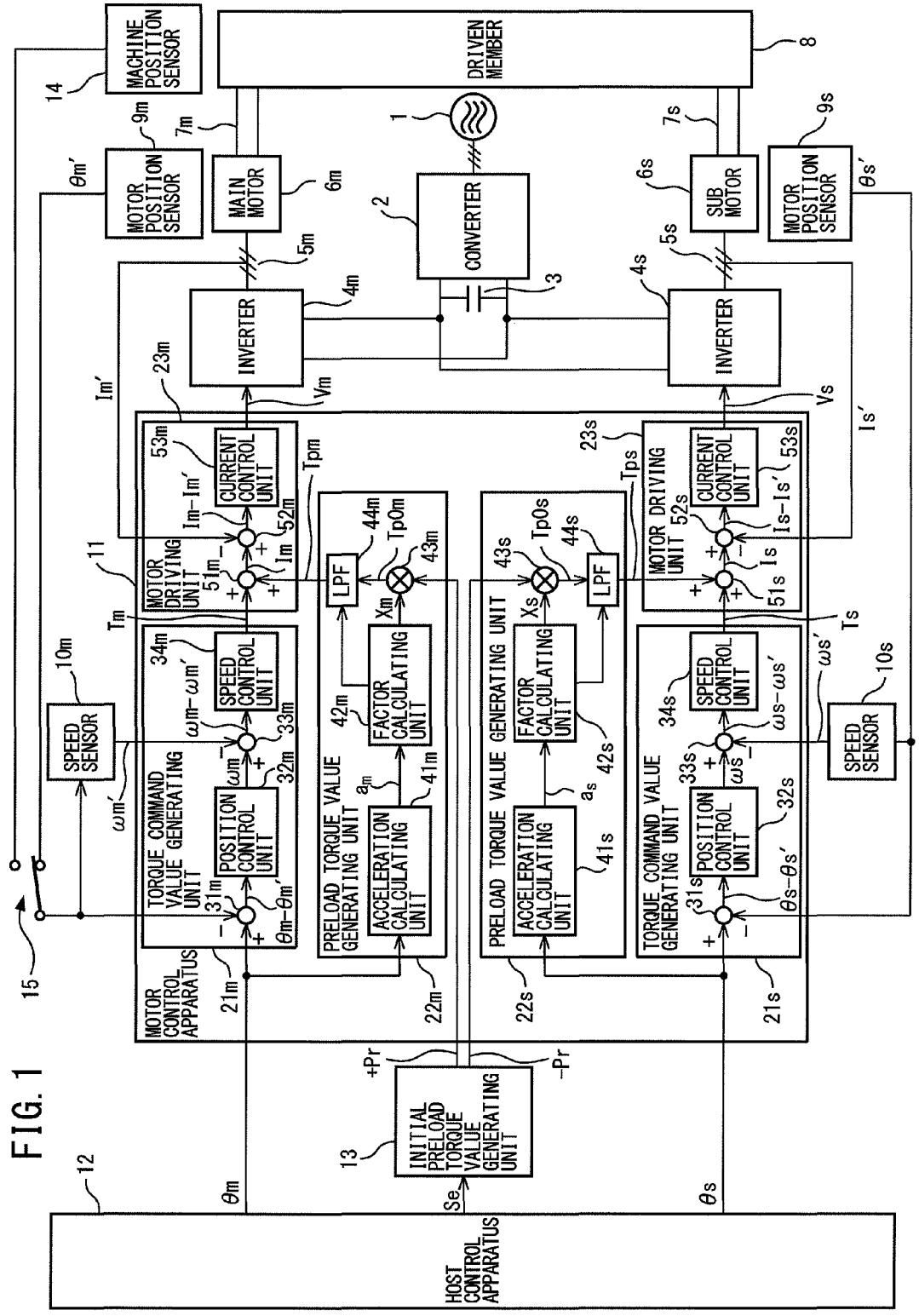

MACHINE POSITION SENSOR
14
DRIVEN MEMBER
8
9m
MOTOR POSITION SENSOR
θm'
7m
MAIN MOTOR
6m
1
CONVERTER
2
3
6s
SUB MOTOR
7s
9s
MOTOR POSITION SENSOR
θs'
5m
INVERTER
4m
4s
5s
INVERTER
Im'
23m
Vm
Vs
Is'
53m
CURRENT CONTROL UNIT
Im-Im'
52m
Tpm
23s
Tps
CURRENT CONTROL UNIT
53s
Is-Is'
11
MOTOR DRIVING UNIT
51m
Im
LPF
44m
TpOm
43m
Xm
43s
TpOs
44s
LPF
MOTOR DRIVING UNIT 52s
Is
51s
Tm
Ts
10m
SPEED SENSOR
ωm'
34m
SPEED CONTROL UNIT
ωm-ωm'
33m
42m
FACTOR CALCULATING UNIT
41m
am
PRELOAD TORQUE VALUE GENERATING UNIT
FACTOR CALCULATING UNIT
42s
as
PRELOAD TORQUE VALUE GENERATING UNIT
41s
ACCELERATION CALCULATING UNIT
ACCELERATION CALCULATING UNIT
34s
SPEED CONTROL UNIT
ωs-ωs'
ωs'
10s
SPEED SENSOR
TORQUE COMMAND VALUE GENERATING UNIT
31m
POSITION CONTROL UNIT
ωm
32m
θm-θm'
TORQUE COMMAND VALUE GENERATING UNIT
33s
ωs
POSITION CONTROL UNIT
32s
31s
θs-θs'
15
MOTOR CONTROL APPARATUS
21m
22m
22s
21s
+Pr
-Pr
13
INITIAL PRELOAD TORQUE VALUE GENERATING UNIT
Se
12
θm
θs
HOST CONTROL APPARATUS

FIG. 1

FIG. 2

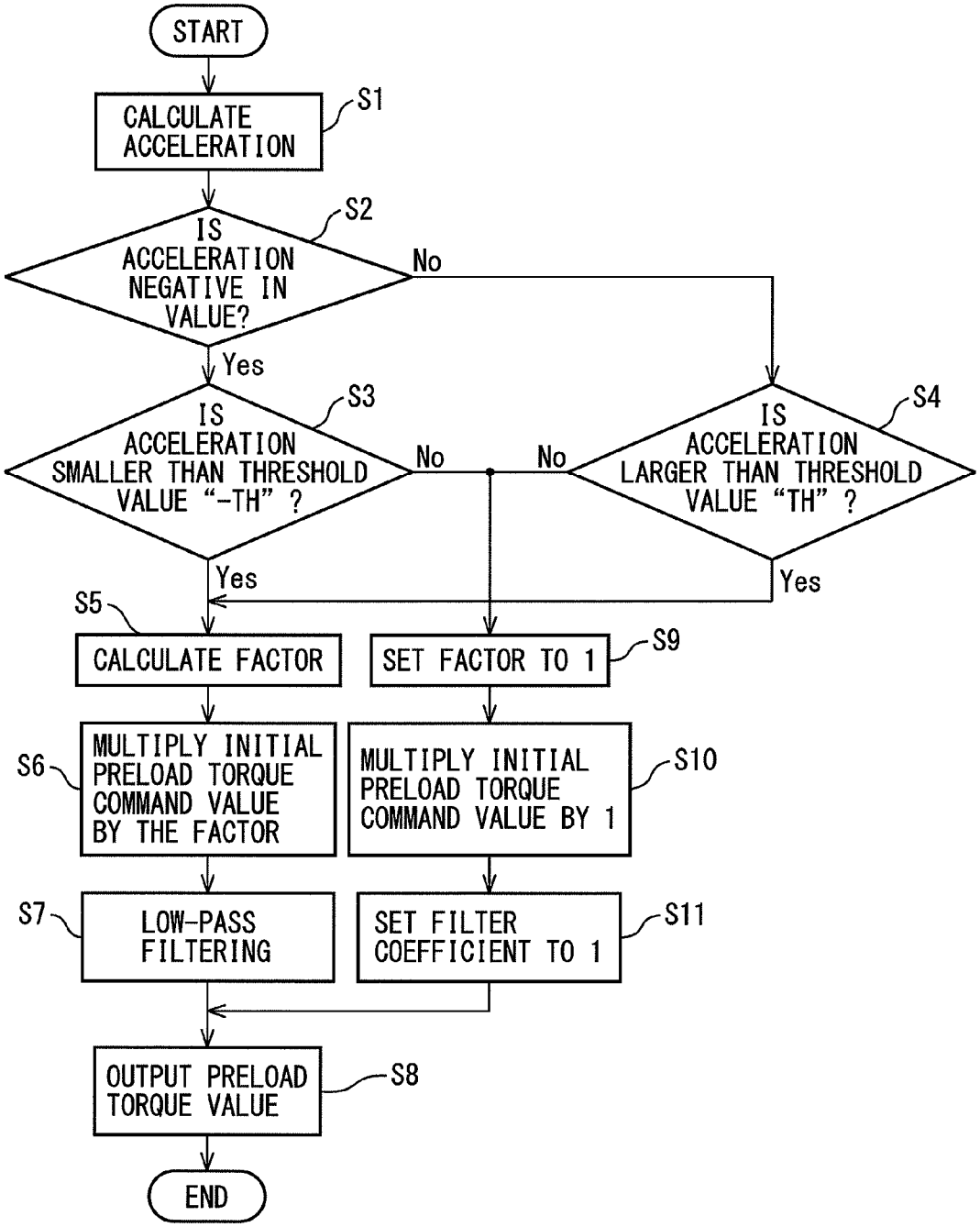

START
CALCULATE ACCELERATION
S1
IS ACCELERATION NEGATIVE IN VALUE?
S2
No
Yes
IS ACCELERATION SMALLER THAN THRESHOLD VALUE "-TH" ?
S3
No
Yes
IS ACCELERATION LARGER THAN THRESHOLD VALUE "TH" ?
S4
No
Yes
S5
CALCULATE FACTOR
SET FACTOR TO 1
S9
S6
MULTIPLY INITIAL PRELOAD TORQUE COMMAND VALUE BY THE FACTOR
MULTIPLY INITIAL PRELOAD TORQUE COMMAND VALUE BY 1
S10
S7
LOW-PASS FILTERING
SET FILTER COEFFICIENT TO 1
S11
OUTPUT PRELOAD TORQUE VALUE
S8
END

FIG. 3A

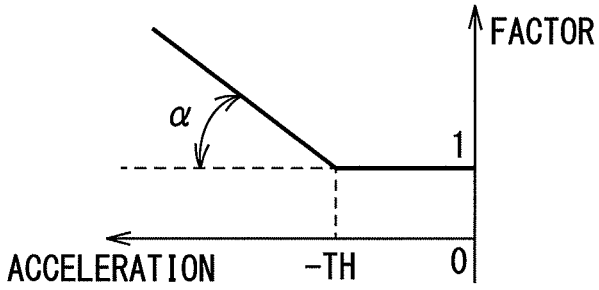


FIG. 3B

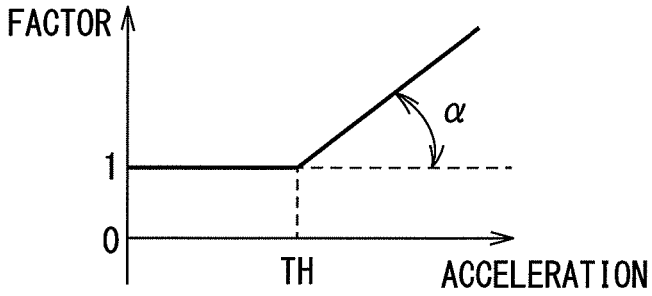


FIG. 4

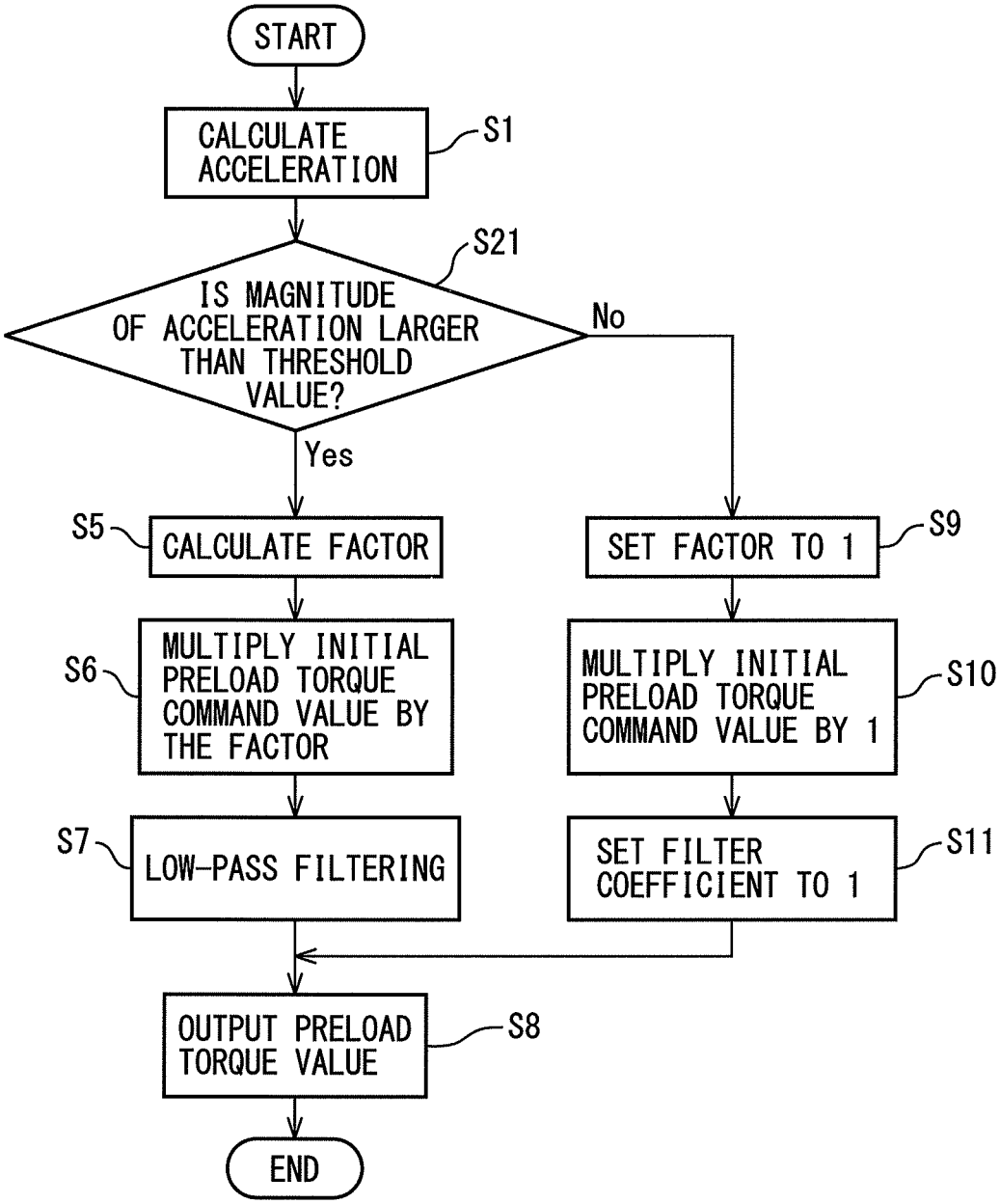

START
CALCULATE ACCELERATION
S1
S21
IS MAGNITUDE OF ACCELERATION LARGER THAN THRESHOLD VALUE?
No
Yes
S5
CALCULATE FACTOR
S9
SET FACTOR TO 1
S6
MULTIPLY INITIAL PRELOAD TORQUE COMMAND VALUE BY THE FACTOR
MULTIPLY INITIAL PRELOAD TORQUE COMMAND VALUE BY 1
S10
S7
LOW-PASS FILTERING
SET FILTER COEFFICIENT TO 1
S11
OUTPUT PRELOAD TORQUE VALUE
S8
END

FIG. 5

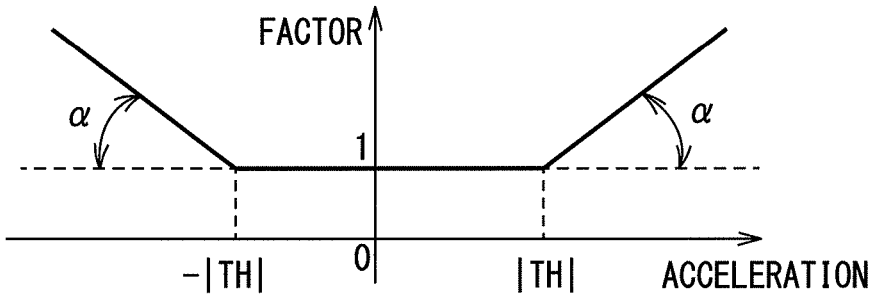
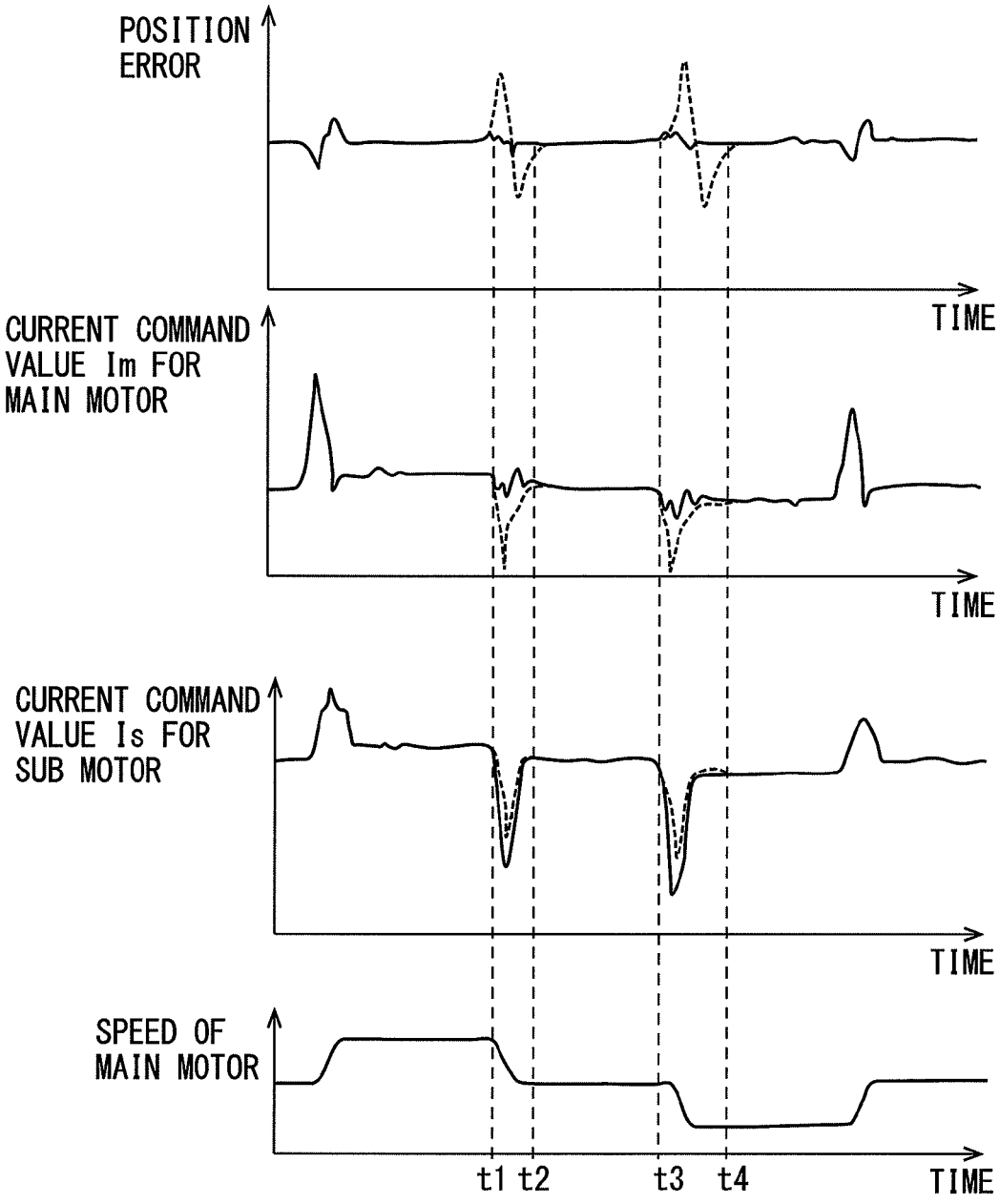


FIG. 6


POSITION ERROR
TIME
CURRENT COMMAND VALUE Im FOR MAIN MOTOR
TIME
CURRENT COMMAND VALUE Is FOR SUB MOTOR
TIME
SPEED OF MAIN MOTOR
t1 t2 t3 t4
TIME

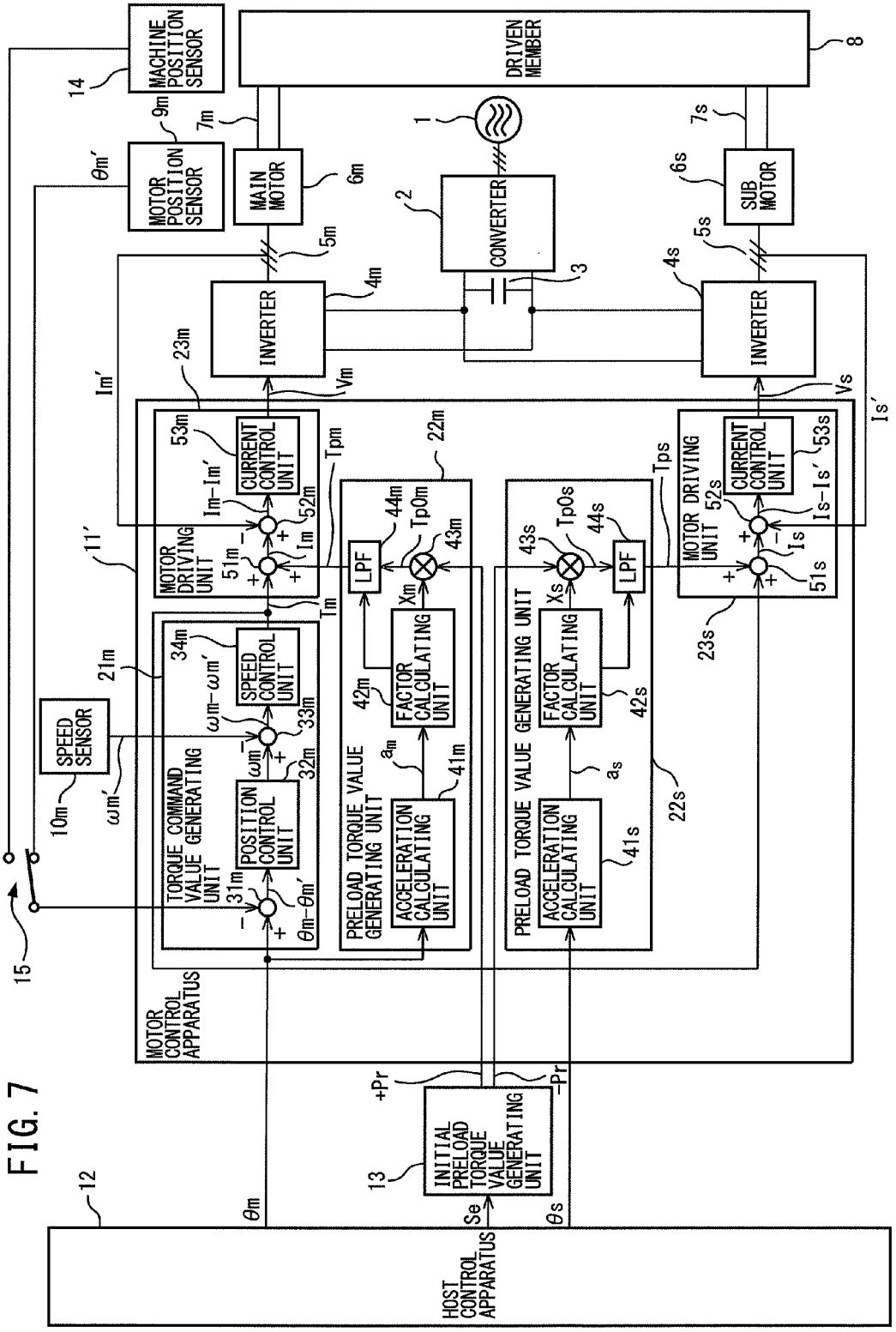

MACHINE POSITION SENSOR
DRIVEN MEMBER
MOTOR POSITION SENSOR
MAIN MOTOR
CONVERTER
SUB MOTOR
INVERTER
INVERTER
MOTOR DRIVING UNIT
CURRENT CONTROL UNIT
CURRENT CONTROL UNIT
MOTOR DRIVING UNIT
SPEED SENSOR
TORQUE COMMAND VALUE GENERATING UNIT
POSITION CONTROL UNIT
SPEED CONTROL UNIT
PRELOAD TORQUE VALUE GENERATING UNIT
ACCELERATION CALCULATING UNIT
FACTOR CALCULATING UNIT
LPF
PRELOAD TORQUE VALUE GENERATING UNIT
ACCELERATION CALCULATING UNIT
FACTOR CALCULATING UNIT
LPF
MOTOR CONTROL APPARATUS
INITIAL PRELOAD TORQUE VALUE GENERATING UNIT
HOST CONTROL APPARATUS

FIG. 7

MOTOR CONTROL APPARATUS THAT GENERATES PRELOAD TORQUE VALUE AS FUNCTION OF MOTOR ACCELERATION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a new U.S. patent application that claims benefit of JP 2013-050817, filed on Mar. 13, 2013, and the entire content of JP 2013-050817 is hereby incorporated by reference.

FIELD OF THE INVENTION

The present invention relates to a motor control apparatus for controlling two motors in order to drive a single driven member.

BACKGROUND OF THE INVENTION

In machine tools or the like, there are cases where a motor-driven member cannot be accelerated or decelerated using a single motor because the driven member is large. There are also cases where the driven member cannot be moved in a stable condition because the backlash between the driven member and the machine element of the transmission mechanism connected to the motor drive shaft is large. In such cases, tandem control is performed in which two motors are used to drive a single driven member (for example, refer to Japanese Unexamined Patent Publications No. JP-A-8-174481, JP-A-2003-79180, or JP-A-2004-92859).

In such tandem control, one of the two motors functions as a main motor having a drive shaft that acts as a master shaft connected to the transmission mechanism. The other one functions as a sub motor having a drive shaft that acts as a slave shaft connected to the transmission mechanism.

There is also proposed a motor drive apparatus that generates a preload torque value when performing tandem control in order to suppress the backlash between the driven member and the machine element of the transmission mechanism connected to the motor drive shaft (for example, refer to Japanese Unexamined Patent Publications No. JP-A-8-16246 or JP-A-2010-172054). The preload torque value is a torque value that is appended in advance to the torque command value so that the direction of force applied to the drive shaft of the main motor and the direction of force applied to the drive shaft of the sub motor will become opposite to each other.

In the motor drive apparatus that generates the preload torque value according to the prior art, the magnitude of the preload torque value is constant, irrespective of the magnitude of acceleration of the main motor or sub motor. As a result, during acceleration/deceleration of the main motor, the acceleration/deceleration torque required on the drive shaft of the main motor may become larger than the preload torque value of the main motor. On the other hand, during acceleration/deceleration of the sub motor, the acceleration/deceleration torque required on the drive shaft of the sub motor may become larger than the preload torque value of the sub motor.

In such cases, either the direction of force applied to the drive shaft of the main motor or the direction of force applied to the drive shaft of the sub motor becomes opposite to the direction of the preload torque applied to suppress the backlash. This can result in an inability to suppress the backlash occurring between the driven member and the machine element of the transmission mechanism connected to the motor drive shaft.

It is an object of the present invention to provide a motor control apparatus which, when driving a single driven member using two motors, can suppress the backlash occurring between the driven member and the machine element of the transmission mechanism connected to the motor drive shaft, even during acceleration/deceleration of the motors.

SUMMARY OF THE INVENTION

According to an embodiment of the present invention, there is provided a motor control apparatus for controlling a first motor and a second motor in order to drive a single driven member, the motor control apparatus comprising: a torque command value generating unit which generates a first torque command value for the first motor and a second torque command value for the second motor, based on at least one set selected from among a set comprising a position command value for the first motor, position information of the first motor, and speed information of the first motor, a set comprising a position command value for the second motor, position information of the second motor, and speed information of the second motor, and a set comprising a position command value for the driven member, position information of the driven member, and speed information of the driven member; a first preload torque value generating unit which calculates first acceleration corresponding to acceleration of the first motor, and generates a first preload torque value as a function of the first acceleration, the first preload torque value being a torque value that is appended in advance to the first torque command value so that the direction of force applied to a drive shaft of the first motor and the direction of force applied to a drive shaft of the second motor will become opposite to each other; a second preload torque value generating unit which calculates second acceleration corresponding to acceleration of the second motor, and generates a second preload torque value as a function of the second acceleration, the second preload torque value being a torque value that is appended in advance to the second torque command value so that the direction of force applied to the drive shaft of the first motor and the direction of force applied to the drive shaft of the second motor will become opposite to each other; a first motor driving unit which drives the first motor based on the first torque command value and the first preload torque value; and a second motor driving unit which drives the second motor based on the second torque command value and the second preload torque value.

Preferably, when the magnitude of the first acceleration exceeds a preset value, the first preload torque value generating unit generates the first preload torque value so that an output torque larger than a first acceleration/deceleration torque required on the drive shaft of the first motor during acceleration/deceleration of the first motor will be produced on the drive shaft of the first motor, and when the magnitude of the second acceleration exceeds a preset value, the second preload torque value generating unit generates the second preload torque value so that an output torque larger than a second acceleration/deceleration torque required on the drive shaft of the second motor during acceleration/deceleration of the second motor will be produced on the drive shaft of the second motor.

Preferably, when the magnitude of the first acceleration exceeds a preset value, the first preload torque value generating unit generates the first preload torque value so that an output torque larger than a first acceleration/deceleration torque required on the drive shaft of the first motor during acceleration/deceleration of the first motor will be produced on the drive shaft of the first motor, and modifies the gener-

ated first preload torque value based on a prescribed time constant, and when the magnitude of the second acceleration exceeds a preset value, the second preload torque value generating unit generates the second preload torque value so that an output torque larger than a second acceleration/deceleration torque required on the drive shaft of the second motor during acceleration/deceleration of the second motor will be produced on the drive shaft of the second motor, and modifies the generated second preload torque value based on a prescribed time constant.

According to an embodiment of the present invention, when driving a single driven member using two motors, the backlash occurring between the driven member and the machine element of the transmission mechanism connected to the motor drive shaft can be suppressed, even during acceleration/deceleration of the motors.

DESCRIPTION OF THE DRAWINGS

These and other features and advantages of the present invention will be better understood by reading the following detailed description, taken together with the drawings wherein:

FIG. **1** is a block diagram of a system incorporating a motor control apparatus according to an embodiment of the present invention;

FIG. **2** is a flowchart illustrating the operation of the motor control apparatus shown in FIG. **1**;

FIG. **3**A is a diagram for explaining how a factor is calculated in the flowchart of FIG. **2**;

FIG. **3**B is a diagram for explaining how a factor is calculated in the flowchart of FIG. **2**;

FIG. **4** is a diagram showing a modified example of the flowchart of FIG. **2**;

FIG. **5** is a diagram for explaining how a factor is calculated in the flowchart of FIG. **4**;

FIG. **6** is a diagram for explaining the advantageous effect of the motor control apparatus according to the present invention; and

FIG. **7** is a block diagram of a system incorporating a motor control apparatus according to another embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Embodiments of motor control apparatus according to the present invention will be described in detail with reference to the drawings. Throughout the drawings, the same component elements will be designated by the same reference numerals. FIG. **1** is a block diagram of a system incorporating a motor control apparatus according to an embodiment of the present invention. The system shown in FIG. **1** includes a three-phase AC power supply **1**, a converter **2**, a smoothing capacitor **3**, inverters **4***m* and **4***s*, current sensors **5***m* and **5***s*, a main motor **6***m* as a first motor, a sub motor **6***s* as a second motor, transmission mechanisms **7***m* and **7***s*, a driven member **8**, motor position sensors **9***m* and **9***s*, speed sensors **10***m* and **10***s*, a motor control apparatus **11**, a host control apparatus **12**, an initial preload torque value generating unit **13**, a machine position sensor **14**, and a position selector **15**.

The three-phase AC power supply **1** is constructed from a commercial AC power supply. The converter **2** comprises, for example, a plurality of rectifier diodes (six in the case of three-phase AC) and transistors connected in reverse parallel with the respective rectifier diodes, and converts the AC power supplied from the three-phase AC power supply **1** into DC power.

The smoothing capacitor **3** is connected in parallel with the converter **2** and smoothes the voltage rectified by the rectifier diodes of the converter **2**. The inverters **4***m* and **4***s* are each connected in parallel with the smoothing capacitor **3**. The inverters **4***m* and **4***s* each comprise, for example, a plurality of rectifier diodes (six in the case of three-phase AC) and transistors connected in reverse parallel with the respective rectifier diodes. The inverters **4***m* and **4***s* convert the DC power output from the converter **2** into AC power by turning the transistors on and off, based on PWM signals Vm and Vs to be described later.

The current sensor **5***m* is provided on the output line of the inverter **4***m* in order to detect the value Im' of the current flowing to the main motor **6***m*. The current sensor **5***s* is provided on the output line of the inverter **4***s* in order to detect the value Is' of the current flowing to the sub motor **6***s*. In the present embodiment, the current sensors **5***m* and **5***s* are each constructed, for example, from a Hall element.

The main motor **6***m* has a drive shaft that acts as a master shaft connected to the transmission mechanism **4***m*, and is driven by the power stored in the smoothing capacitor **3**. The sub motor **6***m* has a drive shaft that acts as a slave shaft connected to the transmission mechanism **4***s*, and is driven by the power stored on the smoothing capacitor **3**.

In the present embodiment, the main motor **6***m* and the sub motor **6***s* are each constructed, for example, from a rotating servo motor in which either the rotor or the stator is a permanent magnet, a linear servo motor in which either the stator or the slider is a permanent magnet, a vibrating servo motor in which either the stator or the vibrator is a permanent magnet, or an induction motor that does not use any permanent magnets.

The transmission mechanisms **7***m* and **7***s* are connected to the driven member **8** in order to move the driven member **8** along the axial direction of the transmission mechanisms **7***m* and **7***s*. The driven member **8** is, for example, a table of a machine tool or an arm of an industrial robot.

The motor position sensor **9***m* is constructed from a rotary encoder, Hall element, resolver, or the like that detects the rotation angle θm' of the main motor **6***m* as the position information of the first motor. The motor position sensor **9***s* is constructed from a rotary encoder, Hall element, resolver, or the like that detects the rotation angle θs' of the sub motor **6***s* as the position information of the second motor.

The speed sensor **10***m* takes as an input the rotation angle θm' of the main motor **6***m* from the motor position sensor **9***m*, obtains the rotational speed ωm' of the main motor **6***m* as the speed information of the first motor by taking the first derivative of the rotation angle θm' with respect to time, and supplies the rotational speed ωm' to the motor control apparatus **11**.

The speed sensor **10***s* takes as an input the rotation angle θs' of the sub motor **6***s* from the motor position sensor **9***s*, obtains the rotational speed ωs' of the sub motor **6***s* as the speed information of the second motor by taking the first derivative of the rotation angle θs' with respect to time, and supplies the rotational speed ωs' to the motor control apparatus **11**.

The motor control apparatus **11** performs tandem control by driving the driven member **8** using the main motor **6***m* and the sub motor **6***s* in order to suppress the torsion of the drive shaft of the main motor **6***m* and the torsion of the drive shaft of the sub motor **6***s* while at the same time reducing the backlash between the driven member **8** and the machine elements of the transmission mechanisms **7***m* and **7***s*. For this

purpose, the motor control apparatus **11** includes two torque command value generating units **21***m* and **21***s* as torque command value generating units, a preload torque command value generating unit **22***m* as a first preload torque command value generating unit, a preload torque command value generating unit **22***s* as a second preload torque command value generating unit, a motor driving unit **23***m* as a first motor driving unit, and a motor driving unit **23***s* as a second motor driving unit.

The torque command value generating unit **21***m* generates a torque command value Tm for the main motor **6***m* as a first torque command value for the first motor, based on a position command value θm for the main motor **6***m* which is supplied as the position command value for the first motor from the host control apparatus **12**, and on the rotation angle θm' which is supplied from the motor position sensor **9***m*. For this purpose, the torque command value generating unit **21***m* includes a subtractor **31***m*, a position control unit **32***m*, a subtractor **33***m*, and a speed control unit **34***m*.

The subtractor **31***m* has a minuend input terminal at which the position command value θm is input from the host control apparatus **12**, a subtrahend input terminal at which the rotation angle θm' is input from the motor position sensor **9***m*, and an output terminal which outputs the position error θm-θm' to the position control unit **32***m*.

To control the position of the main motor **6***m*, the position control unit **32***m* takes the position error θm-θm' as an input from the subtractor **31***m*, and retrieves a position control gain to be used for the main motor **6***m* from a memory (not shown). Then, based on the position error θm-θm' and the position control gain to be used for the main motor **6***m*, the position control unit **32***m* generates a speed command value ωm for the main motor **6***m*, and supplies the generated speed command value ωm to the subtractor **33***m*.

The subtractor **33***m* has a minuend input terminal at which the speed command value ωm is input from the position control unit **32***m*, a subtrahend input terminal at which the rotational speed ωm' is input from the speed sensor **10***m*, and an output terminal which outputs the speed error ωm-ωm' to the speed control unit **34***m*.

To control the speed of the main motor **6***m*, the speed control unit **34***m* takes the speed error ωm-ωm' as an input from the subtractor **33***m*, and retrieves a proportional gain and integral gain to be used for the main motor **6***m* from a memory (not shown). Then, based on the speed error ωm-ωm' and the proportional gain and integral gain to be used for the main motor **6***m*, the speed control unit **34***m* generates a torque command value Tm, and supplies the generated torque command value Tm to the motor driving unit **23***m*.

The torque command value generating unit **21***s* generates a torque command value Ts for the sub motor **6***s* as a second torque command value for the second motor, based on a position command value Os for the sub motor **6***s* which is supplied as the position command value for the second motor from the host control apparatus **12**, and on the rotation angle θs' which is supplied from the motor position sensor **9***s*. For this purpose, the torque command value generating unit **21***s* includes a subtractor **31***s*, a position control unit **32***s*, a subtractor **33***s*, and a speed control unit **34***s*.

The subtractor **31***s* has a minuend input terminal at which the motor position command value Os is input from the host control apparatus **12**, a subtrahend input terminal at which the rotation angle θs' is input from the motor position sensor **9***s*, and an output terminal which outputs the position error θs-θs' to the position control unit **32***s*.

To control the position of the sub motor **6***s*, the position control unit **32***s* takes the position error θs-θs' as an input from the subtractor **31***s*, and retrieves a position control gain to be used for the sub motor **6***s* from a memory (not shown). Then, based on the position error θs-θs' and the position control gain to be used for the sub motor **6***s*, the position control unit **32***s* generates a speed command value ωs for the sub motor **6***s*, and supplies the generated speed command value ωs to the subtractor **33***s*.

The subtractor **33***s* has a minuend input terminal at which the speed command value ωs is input from the position control unit **32***s*, a subtrahend input terminal at which the rotational speed ωs' is input from the speed sensor **10***s*, and an output terminal which outputs the speed error ωs-ωs' to the speed control unit **34***s*.

To control the speed of the sub motor **6***s*, the speed control unit **34***s* takes the speed error ωs-ωs' as an input from the subtractor **33***s*, and retrieves a proportional gain and integral gain to be used for the sub motor **6***s* from a memory (not shown). Then, based on the speed error ωs-ωs' and the proportional gain and integral gain to be used for the sub motor **6***s*, the speed control unit **34***s* generates a torque command value Ts, and supplies the generated torque command value Ts to the motor driving unit **23***s*.

The preload torque value generating unit **22***m* calculates the acceleration a_m of the main motor **6***m* as the first motor acceleration. The preload torque value generating unit **22***m* generates a preload torque value Tpm as a function of the acceleration a_m; the preload torque value Tpm is a torque value that is appended in advance to the torque command value Tm so that the direction of force applied to the drive shaft of the main motor **6***m* and the direction of force applied to the drive shaft of the sub motor **6***s* will become opposite to each other. For this purpose, the preload torque value generating unit **22***m* includes an acceleration calculating unit **41***m*, a factor calculating unit **42***m*, a multiplier **43***m*, and a low-pass filter (LPF) **44***m*.

The acceleration calculating unit **41***m* takes the position command value θm as an input from the host control apparatus **12**, and calculates the acceleration a_m by taking the second derivative of the position command value θm with respect to time. The acceleration calculating unit **41***m* passes the thus calculated acceleration a_m to the factor calculating unit **42***m*.

Based on the acceleration a_m, the factor calculating unit **42***m* calculates the factor Xm by which to multiply the initial preload torque value +Pr that is output as a preset value from the initial preload torque value generating unit **13**.

The multiplier **43***m* takes as inputs the initial preload torque value +Pr from the initial preload torque value generating unit **13** and the factor Xm from the factor calculating unit **42***m*, and produces an intermediate preload value Tp**0***m* as the product of the initial preload torque value +Pr and the factor Xm.

The low-pass filter **44***m* generates the preload torque value Tpm by modifying the intermediate preload value Tp**0***m* based on a prescribed time constant τ which is a preset value. The low-pass filter **44***m* outputs the thus generated preload torque value Tpm to the motor driving unit **23***m*.

The preload torque value generating unit **22***s* calculates the acceleration a_s of the sub motor **6***s* as the second motor acceleration. The preload torque value generating unit **22***s* generates a preload torque value Tps as a function of the acceleration a_s; the preload torque value Tps is a torque value that is appended in advance to the torque command value Ts so that the direction of force applied to the drive shaft of the main motor **6***m* and the direction of force applied to the drive shaft of the sub motor **6***s* will become opposite to each other. For this purpose, the preload torque value generating unit **22***s*

includes an acceleration calculating unit **41***s*, a factor calculating unit **42***s*, a multiplier **43***s*, and a low-pass filter (LPF) **44***s*.

The acceleration calculating unit **41***s* takes the position command value Os as an input from the host control apparatus **12**, and calculates the acceleration a_s by taking the second derivative of the position command value θs with respect to time. The acceleration calculating unit **41***s* passes the thus calculated acceleration a_s to the factor calculating unit **42***s*.

Based on the acceleration a_s, the factor calculating unit **42***s* calculates the factor Xs by which to multiply the initial preload torque value −Pr (i.e., the preload torque value equal in magnitude but opposite in sign to the initial preload torque value +Pr) that is output as a preset value from the initial preload torque value generating unit **13**.

The multiplier **43***s* takes as inputs the initial preload torque value −Pr from the initial preload torque value generating unit **13** and the factor Xs from the factor calculating unit **42***s*, and produces an intermediate preload value Tp**0***s* as the product of the initial preload torque value −Pr and the factor Xs.

The low-pass filter **44***s* generates the preload torque value Tps by modifying the intermediate preload value Tp**0***s* based on the time constant T. The low-pass filter **44***s* outputs the thus generated preload torque value Tps to the motor driving unit **23***s*.

In the present embodiment, the initial preload torque value +Pr, the intermediate preload value Tp**0***m*, and the preload torque value Tpm correspond to the first preload torque value, and the initial preload torque value −Pr, the intermediate preload value Tp**0***s*, and the preload torque value Tps correspond to the second preload torque value.

The motor driving unit **23***m* drives the main motor **6***m*, based on the torque command value Tm and the preload torque value Tpm. For this purpose, the motor driving unit **23***m* includes an adder **51***m*, a subtractor **52***m*, and a current control unit **53***m*.

The adder **51***m* has a first addend input terminal at which the torque command value Tm is input from the speed control unit **34***m*, a second addend input terminal at which the preload torque value Tpm is input from the low-pass filter **44***m*, and an output terminal which outputs the sum of the torque command value Tm and the preload torque value Tpm as the current command value Im for the main motor **6***m*.

The subtractor **52***m* has a minuend input terminal at which the current command value Im is input from the adder **51***m*, a subtrahend input terminal at which the current value Im' is input from the current sensor **5***m*, and an output terminal which outputs a current error Im-Im', i.e., the difference between the current command value Im and the current value Im', to the current control unit **53***m*.

Based on the current error Im-Im' input from the subtractor **52***m*, the current control unit **53***m* generates the PWM signal Vm as the voltage command value for the main motor **6***m*. The current control unit **53***m* supplies the generated PWM signal Vm to the inverter **4***m*.

The motor driving unit **23***s* drives the sub motor **6***s*, based on the torque command value Ts and the preload torque value Tps. For this purpose, the motor driving unit **23***s* includes an adder **51***s*, a subtractor **52***s*, and a current control unit **53***s*.

The adder **51***s* has a first addend input terminal at which the torque command value Ts is input from the speed control unit **34***s*, a second addend input terminal at which the preload torque value Tps is input from the low-pass filter **44***s*, and an output terminal which outputs the sum of the torque command value Ts and the preload torque value Tps as the current command value Is for the sub motor **6***s*.

The subtractor **52***s* has a minuend input terminal at which the current command value Is is input from the adder **51***s*, a subtrahend input terminal at which the current value Is' is input from the current sensor **5***s*, and an output terminal which outputs a current error Is-Is', i.e., the difference between the current command value Is and the current value Is', to the current control unit **53***s*.

Based on the current error Is-Is' input from the subtractor **52***s*, the current control unit **53***s* generates the PWM signal Vs as the voltage command value for the sub motor **6***s*. The current control unit **53***s* supplies the generated PWM signal Vs to the inverter **4***s*.

The host control apparatus **12**, which is, for example, a computer numerically controlled (CNC) apparatus or the like, supplies the position command value θm to the subtractor **31***m* and the acceleration calculating unit **41***m* and the position command value θs to the subtractor **31***s* and the acceleration calculating unit **41***s*, and also supplies an excitation signal Se for generating the initial preload torque values +Pr and −Pr to the initial preload torque value generating unit **13**.

In response to the excitation signal Se from the host control apparatus **12**, the initial preload torque value generating unit **13** generates the initial preload torque values +Pr and −Pr and supplies the thus generated initial preload torque values +Pr and −Pr to the multipliers **43***m* and **43***s*, respectively.

The machine position sensor **14** is constructed from a scale, etc. for detecting, as the position information of the driven member, the position of the machine (not shown) containing the transmission mechanisms **7***m* and **7***s*. The position selector **15** includes a switch for connecting the subtrahend input terminal of the subtractor **31***m* to either the motor position sensor **9***m* or the machine position sensor **14** in accordance with a command entered from an operation unit (not shown).

In the system shown in FIG. **1**, the position selector **15** is set to connect the subtrahend input terminal of the subtractor **31***m* to the motor position sensor **9***m*, and the present embodiment has been described for the case where the subtrahend input terminal of the subtractor **31***m* is connected by the position selector **15** to the motor position sensor **9***m*.

When the position selector **15** is set to connect the subtrahend input terminal of the subtractor **31***m* to the machine position sensor **14**, the position of the machine (not shown) detected by the machine position sensor **14** is input as the position information of the driven member to the subtrahend input terminal of the subtractor **31***m*. The speed of the driven member **8** is detected by the speed sensor **10***m* and input as the speed information of the driven member to the subtrahend input terminal of the subtractor **33***m*. The host control apparatus **12** outputs the position command value for the machine (not shown) which is input as the position command value for the driven member to the minuend input terminal of the subtractor **33***m*.

In the present embodiment, the speed sensors **10***m* and **10***s*, the motor control apparatus **11**, and the initial preload torque value generating unit **13** are implemented by a processor equipped with input/output ports, a serial communication circuit, an A/D converter, a comparator, etc., and the process—to be described later—is performed in accordance with a processing program stored in a memory (not shown).

FIG. **2** is a flowchart illustrating the operation of the motor control apparatus shown in FIG. **1**. The flowchart is carried out under the control of a processing program executed on the motor control apparatus **11**, each time the initial preload torque value generating unit **13** generates the initial preload torque values +Pr and −Pr in response to the excitation signal Se.

First, the acceleration calculating unit **41***m*, **41***s* calculates the acceleration a_m, a_s, and passes the calculated acceleration a_m, a_s to the factor calculating unit **42***m*, **42***s* (step S**1**). After that, the factor calculating unit **42***m*, **42***s* determines whether the calculated acceleration a_m, a_s is negative in value or not (step S**2**). If the acceleration a_m, a_s is negative in value, the factor calculating unit **42***m*, **42***s* then determines whether the acceleration a_m, a_s is smaller than a threshold value −TH (TH is a positive value) which is a preset value (step S**3**). On the other hand, if the acceleration a_m, a_s is not smaller in value than zero, the factor calculating unit **42***m*, **42***s* then determines whether the acceleration a_m, a_s is larger than a threshold value TH (step S**4**).

If the acceleration a_m, a_s is smaller than the threshold value −TH, or if the acceleration a_m, a_s is larger than the threshold value TH, the factor calculating unit **42***m*, **42***s* calculates the factor Xm, Xs, and supplies the calculated factor Xm, Xs to the multiplier **43***m*, **43***s*. In the present embodiment, when the acceleration a_m, a_s is smaller than the threshold value −TH, the factor calculating unit **42***m*, **42***s* calculates the factor Xm, Xs by using the following equation (1) or (2), respectively.

$$Xm=1+(a_m+TH)\alpha \quad (1)$$

$$Xs=1+(a_s+TH)\alpha \quad (2)$$

In the equations (1) and (2), α represents the slope to be described later. On the other hand, when the acceleration a_m, a_s is larger than the threshold value TH, the factor calculating unit **42***m*, **42***s* calculates the factor Xm, Xs by using the following equation (3) or (4), respectively.

$$Xm=1+(a_m-TH)\alpha \quad (3)$$

$$Xs=1+(a_s-TH)\alpha \quad (4)$$

Next, the multiplier **4***m* produces the intermediate preload value Tp**0***m* by taking the product of the initial preload torque value +Pr and the factor Xm, and supplies the produced intermediate preload value Tp**0***m* to the low-pass filter **44***m*. The multiplier **4***s* produces the intermediate preload value Tp**0***s* by taking the product of the initial preload torque value −Pr and the factor Xs, and supplies the produced intermediate preload value Tp**0***s* to the low-pass filter **44***s* (step S**6**).

The low-pass filter **44***m* performs filtering in order to generate the preload torque value Tpm by modifying the intermediate preload value Tp**0***m* based on the time constant τ, and outputs the thus generated preload torque value Tpm to the adder **51***m*. The low-pass filter **44***s* performs filtering in order to generate the preload torque value Tps by modifying the intermediate preload value Tp**0***s* based on the time constant τ (step S**7**), and outputs the thus generated preload torque value Tps to the adder **51***s* (step S**8**), after which the process flow is terminated.

In the present embodiment, the preload torque values Tpm and Tps can be expressed by the following equations (5) and (6), respectively.

$$Tpm=k\cdot Tpm+(1-k)Tp0m \quad (5)$$

$$Tps=k\cdot Tps+(1-k)Tp0s \quad (6)$$

$$k=1-e^{-(T/\tau)}$$

where T is the sampling period, and k is the coefficient calculated based on the time constant τ and sampling period T when performing filtering.

On the other hand, if it is determined in step S**3** that the acceleration a_m, a_s is not smaller than the threshold value −TH, or if it is determined in step S**4** that the acceleration a_m, a_s is not larger than the threshold value TH, the factor calculating unit **42***m*, **42***s* sets the factor Xm, Xs to 1 (step S**9**).

Next, the multiplier **43***m* multiplies the initial preload torque value +Pr by the factor Xm, i.e., 1, and supplies the intermediate preload torque value Tp**0***m* corresponding to the initial preload torque value +Pr to the low-pass filter **44***m*. The multiplier **43***s* multiplies the initial preload torque value −Pr by the factor Xs, i.e., 1, and supplies the intermediate preload torque value Tp**0***s* corresponding to the initial preload torque value −Pr to the low-pass filter **44***s* (step S**10**).

Next, the factor calculating unit **42***m*, **42***s* sets the filter coefficient for the low-pass filter **44***m*, **44***s* to 1 (step S**11**), after which the process proceeds to step S**8**

FIGS. **3**A and **3**B are diagrams for explaining how the factor is calculated in the flowchart of FIG. **2**. When the acceleration is negative in value, the factor is fixed to 1 as long as the acceleration is not smaller than the threshold value −TH, as indicated by a solid line in FIG. **3**A. When the acceleration is smaller than the threshold value −TH, the factor increases in proportion to the slope α as the acceleration decreases.

On the other hand, when the acceleration is zero or positive in value, the factor is fixed to 1, as long as the acceleration is not larger than the threshold value TH, as indicated by a solid line in FIG. **3**B; when the acceleration is larger than the threshold value TH, the factor increases in proportion to the slope α as the acceleration increases.

By thus varying the factor in proportion to the slope α, when the acceleration becomes smaller than the threshold value −TH or becomes larger than the threshold value TH, the torque command value generating unit **21***m* generates the preload torque value Tpm so that an output torque larger than the acceleration/deceleration torque, i.e., the first acceleration/deceleration torque, required on the drive shaft of the main motor **6***m* during acceleration/deceleration of the main motor **6***m* will be produced on the drive shaft of the main motor **6***m*. On the other hand, the torque command value generating unit **21***s* generates the preload torque value Tps so that an output torque larger than the acceleration/deceleration torque, i.e., the second acceleration/deceleration torque, required on the drive shaft of the sub motor **6***s* during acceleration/deceleration of the sub motor **6***s* will be produced on the drive shaft of the sub motor **6***s*.

FIG. **4** is a diagram showing a modified example of the flowchart of FIG. **2**. The flowchart process shown here is carried out under the control of a processing program executed on the motor control apparatus **11**, each time the initial preload torque value generating unit **13** generates the initial preload torque values +Pr and −Pr in response to the excitation signal Se.

In the flowchart shown in FIG. **4**, after step S**1**, the factor calculating unit **42***m*, **42***s* determines whether the absolute value of the calculated acceleration a_m, a_s is larger than the threshold value TH (step S**21**). If the absolute value of the acceleration a_m, a_s is larger than the threshold value TH, the process proceeds to step S**5**. On the other hand, if the absolute value of the acceleration a_m, a_s is not larger than the threshold value TH, the process proceeds to step S**9**.

FIG. **5** is a diagram for explaining how the factor is calculated in the flowchart of FIG. **4**. When the absolute value of the acceleration is not larger than the threshold value TH, the factor is fixed to 1, as indicated by a solid line in FIG. **5**, and when the absolute value of the acceleration is larger than the threshold value TH, the factor increases in proportion to the slope α as the absolute value of the acceleration increases.

By thus varying the factor in proportion to the slope α, when the absolute value of the acceleration becomes larger than the threshold value TH, the torque command value generating unit **21***m* generates the preload torque value Tpm so

that an output torque larger than the acceleration/deceleration torque required on the drive shaft of the main motor **6***m* during acceleration/deceleration of the main motor **6***m* will be produced on the drive shaft of the main motor **6***m*. On the other hand, the torque command value generating unit **21***s* generates the preload torque value Tps so that an output torque larger than the acceleration/deceleration torque required on the drive shaft of the sub motor **6***s* during acceleration/deceleration of the sub motor **6***s* will be produced on the drive shaft of the sub motor **6***s*.

FIG. **6** is a diagram for explaining the advantageous effect of the motor control apparatus according to the present invention. FIG. **6** shows, in order from top to bottom, a graph showing how the position error changes with time, a graph showing how the current command value Im for the main motor **6***m* changes with time, a graph showing how the current command value Is for the sub motor **6***s* changes with time, and a graph showing how the speed of the main motor **6***m* changes with time.

When a constant preload torque value is generated irrespective of changes in motor acceleration, the position error, the current command value Im for the main motor **6***m*, and the current command value Is for the sub motor **6***s* change as indicated by broken lines. More specifically, during the deceleration of the main motor **6***m* over the period from time t**1** to time t**2**, and during the deceleration of the main motor **6***m* over the period from time t**3** to time t**4**, the fluctuation of the position error increases, resulting in an inability to suppress the backlash occurring between the driven member **8** and the machine elements of the transmission mechanisms **7***m* and **7***s* connected to the main motor **6***m* and sub motor **6***s*, respectively.

By contrast, when the preload torque value Tpm, Tps is generated in such a manner as to respond to changes in acceleration a_m, a_s, the position error, the current command value Im for the main motor **6***m*, and the current command value Is for the sub motor **6***s* change as indicated by solid lines. More specifically, during the deceleration of the main motor **6***m* over the period from time t**1** to time t**2**, and during the deceleration of the main motor **6***m* over the period from time t**3** to time t**4**, the fluctuation of the position error remains low, thus making it possible to suppress the backlash occurring between the driven member **8** and the machine elements of the transmission mechanisms **7***m* and **7***s* connected to the main motor **6***m* and sub motor **6***s*, respectively.

According to the present embodiment, since the preload torque value Tpm, Tps is generated in such a manner as to respond to changes in acceleration a_m, a_s, the backlash between the driven member **8** and the machine elements of the transmission mechanisms **7***m* and **7***s* can be suppressed, even during the acceleration/deceleration of the main motor **6***m* and sub motor **6***s* when driving the driven member **8** using the main motor **6***m* and sub motor **6***s*.

Further, according to the present embodiment, the preload torque value Tpm, Tps is maintained at a constant value, as long as the absolute value of the acceleration a_m, a_s is not larger than the threshold value TH, and when the absolute value of the acceleration a_m, a_s exceeds the threshold value TH, the preload torque value Tpm, Tps is increased as the absolute value of the acceleration a_m, a_s increases. This serves to avoid a situation where excessive preload torque values Tpm and Tps are added to the torque command values Tm and Ts and applied to the drive shafts of the main motor **6***m* and sub motor **6***s*, respectively, when the main motor **6***m* and sub motor **6***s* are in a stopped condition or when the main motor **6***m* and sub motor **6***s* are running at constant speed.

Furthermore, according to the present embodiment, the preload torque values Tpm and Tps are generated by modifying the intermediate preload torque values Tp**0***m* and Tp**0***s*, respectively, based on the time constant τ. As a result, the impact caused by the backlash occurring between the driven member **8** and the machine elements of the transmission mechanisms **7***m* and **7***s* can be reduced.

FIG. **7** is a block diagram of a system incorporating a motor control apparatus according to another embodiment of the present invention. The system shown in FIG. **7** includes a three-phase AC power supply **1**, a converter **2**, a smoothing capacitor **3**, inverters **4***m* and **4***s*, current sensors **5***m* and **5***s*, a main motor **6***m* as a first motor, a sub motor **6***s* as a second motor, transmission mechanisms **7***m* and **7***s*, a driven member **8**, a motor position sensor **9***m*, a speed sensor **10***m*, a motor control apparatus **11'**, a host control apparatus **12**, an initial preload torque value generating unit **13**, a machine position sensor **14**, and a position selector **15**.

The motor control apparatus **11'** includes a single torque command value generating unit **21***m* as a torque command value generating unit, a preload torque command value generating unit **22***m*, a preload torque command value generating unit **22***s*, a motor driving unit **23***m*, and a motor driving unit **23***s*.

In the present embodiment, the torque command value Tm for the main motor **6***m* and sub motor **6***s* is supplied from the speed control unit **34***m* to the adders **51***m* and **51***s* as the first torque command value for the first motor and the second torque command value for the second motor, respectively.

According to the present embodiment, the motor control apparatus itself and the system incorporating the motor control apparatus can be simplified in order to implement the motor control apparatus according to the present invention.

The present invention is not limited to the above particular embodiments, and many changes and modifications can be made to the embodiments. For example, while the above embodiments have been described for the case where the acceleration a_m, a_s is calculated based on the position command value θm, θs, the acceleration a_m, a_s may be calculated based on the rotation angle θm', θs'.

The above embodiments have been described as having a configuration that includes the low-pass filters **44***m* and **44***s*. However, the low-pass filters **44***m* and **44***s* may be omitted.

Further, while the above embodiments have been described in the case where the acceleration values a_m and a_s are both calculated and the factors Xm and Xs are calculated using the respective acceleration values a_m and a_s, the present invention is also applicable in the case where only one or the other of the acceleration values, a_m or a_s, is calculated and the factors Xm and Xs are calculated using the calculated acceleration value a_m or a_s.

The above embodiments have also been described in the case where the torque command values Tm and Ts are generated based on two sets, one comprising the position command value θm, rotation angle θm', and rotational speed ωm' and the other comprising the position command value Os, rotation angle θs', and rotational speed ωs', and the case where the torque command values Tm and Ts are generated based on the set comprising the position command value θm, rotation angle θm', and rotational speed ωm'. However, the torque command values Tm and Ts may be generated based on at least one set selected from among the set comprising the position command value θm, rotation angle θm', and rotational speed ωm', the set comprising the position command value Os, rotation angle θs', and rotational speed ωs', and the set comprising the position command for the machine not

shown, the position information of the machine not shown, and the speed information of the driven member **8**.

What is claimed is:

1. A motor control apparatus for tandem control of a first motor and a second motor in order to drive single driven member, said motor control apparatus comprising:

a torque command value generating unit which generates a first torque command value for said first motor and a second torque command value for said second motor, based on at least one set selected from among a set comprising a position command value for said first motor, position information of said first motor, and speed information of said first motor, a set comprising a position command value for said second motor, position information of said second motor, and speed information of said second motor, and a set comprising a position command value for said driven member, position information of said driven member, and speed information of said driven member;

a first preload torque value generating unit which calculates first acceleration corresponding to acceleration of said first motor, and calculates a first preload torque value to be a value which is proportional to an absolute value of said first acceleration and is larger than said first torque command value, said first preload torque value being a torque value that is appended in advance to said first torque command value so that the direction of force applied to a drive shaft of said first motor and the direction of force applied to a drive shaft of said second motor will become opposite to each other;

a second preload torque value generating unit which calculates second acceleration corresponding to acceleration of said second motor, and calculates a second preload torque value to be a value which is proportional to an absolute value of said second acceleration and is larger than said second torque command value, said second preload torque value being a torque value that is appended in advance to said second torque command value so that the direction of force applied to the drive shaft of said first motor and the direction of force applied to the drive shaft of said second motor will become opposite to each other;

a first motor driving unit which drives said first motor based on said first torque command value and said first preload torque value; and

a second motor driving unit which drives said second motor based on said second torque command value and said second preload torque value.

2. The motor control apparatus according to claim **1**, wherein

when a predetermined threshold value is positive and when the magnitude of said first acceleration exceeds said threshold value, or when said threshold value is negative and when the magnitude of said first acceleration is less than said threshold value the first preload torque value generating unit generates said first preload torque value so that an output torque larger than a first acceleration/deceleration torque required on the drive shaft of said first motor during acceleration/deceleration of said first motor will be produced on the drive shaft of said first motor, and when the predetermined threshold value is positive and when the magnitude of said second acceleration exceeds said threshold value, or when said threshold value is negative and when the magnitude of said second acceleration is less than said threshold value the second preload torque value generating unit generates said second preload torque value so that an output torque larger than a second acceleration/deceleration torque required on the drive shaft of said second motor during acceleration/deceleration of said second motor will be produced on the drive shaft of said second motor.

3. The motor control apparatus according to claim **1**, wherein the first preload torque value generating unit performs low-pass filtering said generated first preload torque value the second preload torque value generating unit performs low-pass filtering said generated second preload torque value.

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